Design of 50 kw Permanent Magnet Synchronous Motor for HEV

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Abstract -- Hybrid electric vehicle (HEV) has much lower emissions compared to conventional gasoline powered vehicles. Permanent magnet synchronous machines are known as a good candidate for hybrid electric vehicles due to their unique merits. In this research paper an optimal design of a permanent magnet machine is presented. A reduction of permanent magnet material for a constant torque and an extension in speed and torque ranges are chosen as the optimization aims. As the high field strength of neodymium-iron-boron (NdFeB) magnets become commercially available with affordable prices, PMSMs are receiving increasing attention due to their high speed, high power density and high efficiency. In this research paper, 50 kW, 3000 r.p.m permanent magnet synchronous motor is designed.

Indexed Terms: HEV, synchronous, permanent, magnet, speed, torque

I. INTRODUCTION

Hybrid vehicles are the ones with more than one type of power plant which supplies energy to the vehicle. These power supplies could be spark ignition engines, diesel/compress-ignition engines, gas turbines, electric motors, fuel-cells, batteries etc. Moreover, hybrid electric vehicles (HEVs), which are the main concern of this research, are the ones utilizing the electric motor (EM) as the second power plant.

The main reasons for conducting research on HEVs are to improve the fuel efficiency of the vehicles and to decrease the emissions in the urban areas, especially in cities with high population and traffic. Furthermore, the decrease in fuel consumption could be enhanced with proper design of power-train components, such as downsizing the internal combustion engines (ICEs) and applying continuous variable transmission which could be optimized for better fuel consumption performance, and well-selected power management strategies for the vehicle like regaining the kinetic energy lost during braking through EM or driving the vehicle with EM at the start-up of the trip where ICE are known to be inefficient, etc. In fact, these power management strategies depending on the characteristics of the prime mover and the auxiliary power-plant used make the major improvement over the desired performance of the vehicle as the increased complexity of these vehicles with the extra components on the drive-train prevents the expected outcomes of the individual components to the total efficiency [1].

II. HYBRID SYSTEM

The conception hybrid, related to motor vehicles, is a vehicle equipped with more than one energy transformer. By this definition it is not stated which type of energy transformers are used in the hybrid system. However, this does not mean that the number and types of energy transformers are unlimited when looking at practical, technical and economical possibilities. Fuel cells may, for example, be used in hybrid vehicles and such vehicles are already presented as prototypes, but are not today either so technically well developed or economically feasible as to be introduced on the market. The aim here is to describe the main alternatives of hybrid systems in greater detail, in order to provide information for those readers who are familiar with the hybrid technology for motor vehicles.

It is usual today to have an internal combustion engine connected to an electric generator used as one of the (or the main) energy transformer system and a battery in combination with an electric motor as the other energy transformer system. The engine can most commonly be an otto engine or a diesel engine but other alternatives are possible such as sterling engines, gas turbines etc.

There are many different types of battery available such as special lead (acid) batteries, a valve regulated lead accumulator, nickel metal hydride batteries

(NiMH), natrium (sodium)-nickel chlorine batteries, zinc air batteries, lithium-ion and lithium-polymer batteries respective and some others. The use of capacitors and especially ultra-capacitors constitutes an important possibility of storing electric energy.

The combination fuel cell and battery is a possible and attractive long-term alternative combination in hybrid vehicles. However, an even more attractive alternative would be a vehicle where the fuel cell is directly connected to the electric motor as the fuel cell can itself be regarded as a battery. The problem associated with such a system seems to be that electric energy is commonly not stored in a fuel cell system, such as the one mentioned, and therefore the fuel cells must rapidly convert the chemical energy in the fuel to electric energy, since the fuel cells has to produce a variably flow of electricity. However, the energy efficiency of such a vehicle can exceed quite considerably that of a vehicle having both a fuel cell and a battery. As already described there are three main types of hybrid systems, classified as series hybrids, parallel hybrids and series-parallel hybrids [2].

Hybrid electric vehicles are classified three types according to the division of power between the two energy sources in the drive train. These are:
1. Series hybrid system.
2. Parallel hybrid system.
3. Series-parallel hybrid system.

III. DESIGN CONSIDERATIONS PROCEDURE

Synchronous machines are designed to achieve the following information regarding its various parts supply.
a) Main dimensions of stator frame
b) Complete details of the stator winding
c) Details Design of the PM rotor
d) Performance of the designed parts, in order to justify the design of the above parts

To carry out the design for obtaining the above information, the followings are needed.
a) Detailed specifications of the synchronous machines
b) Design equations, based on which the design is initiated
c) Proper information for choosing justified values of various design parameters, such as specific magnetic loading, specific electronic loading etc,
d) Knowledge of available materials, magnetic, insulating, conducting and their typical behavior
e) Limiting values of various performance parameters, such as iron losses, efficiency, short circuit current etc,

Design of electrical machines mainly consists of obtaining the dimensions of the various parts of the machine to suit given specifications, using available material economically and then to furnish these data to the manufacture of the machine. The aim of the designer is to obtain: lower cost, smaller size, wider temperature limit, lower weight, better performance under no load and loaded conditions, minimum losses.

IV. SPECIFICATIONS OF THREE-PHASE SYNCHRONOUS MOTOR

Important specifications or input design data needed to initiate the design are as follows;
a) Rated output
b) Rated voltage
c) Speed
d) Frequency
e) Type of synchronous machine (salient or non-salient pole)
f) Connection of stator winding
g) Limit of temperature

1. Main Dimensions of Stator Frame

Internal diameter and gross length of the stator frame are its main dimensions. It is essential to develop an equation connecting the output of synchronous machine with its main dimensions in order to estimate the latter.

Output Equation

For the synchronous motor,

$$D = \sqrt[3]{\frac{6.1 \times P' \times 10^{7}}{\alpha_i \times K_f \times K_w \times A \times B_g \times n \times \lambda}}$$

$$D^2L = \frac{6.1\times10^7\times P'}{\alpha_i K_f K_w A B_g n}$$

$L = \lambda\times D$

where D = Internal diameter of stator, cm
L = Gross length of stator, cm
P' = designing power, kW
α_i = pole spanning coefficient (calculations)
α_p = pole spanning coefficient (construction)
K_f = form factor
K_w = stator winding factor
A = electromagnetic load, A/cm
B_g = air-gap flux density, T
n = speed, rpm
λ = stack aspect ratio

$$P' = K_E P_n \quad (3)$$

$$P_n = \frac{P_L}{\eta} \quad (4)$$

where P_n = input power, W
P_L = output power, W
K_E = coefficient of apparent power

$$\alpha_i = 0.485+0.4\alpha_p \quad (5)$$

Relation between D and L

Internal diameter and gross length of the stator can be calculated from the product D^2L. And a suitable relation is assumed between D and L.

For round pole- The ratio of pole arc to pole pitch may be assumed from 0.6 to 0.7 and pole arc may be taken equal to the axial length of the stator core

$$\frac{\text{Axial length of the core}}{\text{Pole pitch}} = \frac{L}{\tau_p} = 0.6 \text{ to } 0.7$$

For rectangular pole- The ratio of axial length of the core to pole pitch varies from 0.8 to 3. A suitable ratio may be assumed for axial length to pole pitch depending upon the design specification.

$$\frac{L}{\tau_p} = 0.8 \text{ to } 3$$

Length of Air Gap

The length of air gap in synchronous machines is an important design parameter because its value greatly influences the performance of the machine.

The longer length of air gap will require increased values of field mmf making the machine costly. The length of air gap l_g is related to pole-pitch τ_p as below;

(1) Salient pole machines with open type slots,

$$\frac{l_g}{\tau_p} = 0.01 \text{ to } 0.015$$

(2) For turbo machine,

$$\frac{l_g}{\tau_p} = 0.02 \text{ to } 0.025$$

V. DESIGN OF STATOR WINDING

Stator winding consists of single turn or multi turn coils, suitably arranged in slots and connected properly, so as to obtain the required phase grouping. Winding must be properly arranged, so that the e.m.f induced in all the phases are of equal magnitude and frequency. The e.m.fs of all phases must have identical wave shape and displaced in time phase by 120˚.

Number of Slots

The number of stator slots should be properly chosen, as it affects the cost and performance of synchronous machine. Though, there are no definite rules for deciding the number of stator slots, but the discussion given below will be quite helpful in deciding the proper number. Slot pitch, which depends upon the number of slots, should have approximately the following values for different cases.

– For low voltages machine: Less than or equal to 3.5 cm
– For machines up to 6 KV: Less than or equal to 5.5 cm
– For machines up to 15 KV: Less than or equal to 7.5 cm

Normally, the number of poles is quite large in salient pole synchronous machine and the number of slots per pole per phase may be assumed as 3.

Turns per Phase

Number of turns per phase can be calculated, using the emf equation of synchronous machines.

Number of stator slots per pole = 3q

Total number of stator slots, N_s = 3pq

where q = number of stator slots per pole per phase

Conductors per slot,

$$C_s = \frac{\pi DA}{I_{ph} N_s}$$

Turns per phase,

$$W_{ph} = \frac{K_E V_{ph}}{4 K_f K_w f \phi}$$

$$K_q = \frac{\sin\frac{\pi}{6}}{q \sin\frac{\pi}{6q}}$$

$$K_y = \sin\frac{\pi y}{2\tau_p}$$

$$K_w = K_q K_y$$

The pole pitch, $\tau_p = \frac{\pi D}{p}$

where τ_p = pole pitch, m

y = number of slots per pole

Air gap flux per pole,

$$\phi = \alpha_i \tau_p L B_g \times 10^{-4} \text{ Wb}$$

Stator winding factor, K_w may be assumed as per the winding details. For full pitch coils with infinitely distributed winding, stator winding factor, K_w is equal to 0.955. The number of turns should be an integer.

Conductor Section

Sectional area of the conductor for the stator winding can be based on the stator current per phase and operating current density for the stator winding.

Sectional area of conductor,

$$a_s = \frac{I_s}{J_s}$$

Current density, J_s should be assumed as per the cooling system used. Usual values for the current density in the stator winding can be assumed varying from 5 to 8 A per mm^2.

Stator Coils

The stator winding of alternators utilizes two types of coils (1) single turn bar (2) multi-turn.

Dimensions of Stator Slot

As the number of stator slots, type of winding, it is possible to estimate the width and depth of the slot. Limiting value of the width of slot is sharply dependent upon the rated terminal voltage of the alternator.

For rated voltages ranging from 11kV to 16 kV, the width of the stator slot generally varies from 1.7cm to 2.4cm.

For lower rated voltages, width of slot will vary between 1.2cm to 1.6cm.

The maximum economical width of the stator slot for high voltage alternators is about 2.4 cm.

The depth of stator slot for rated voltages of 11 to 16 kV will normally vary between 12.5cm to 16.5 cm.

For lower voltages, its variation will be in the range of 7.0 cm to 12.0 cm.

Width of the slot can be determined during a particular design, based upon the slot pitch and tooth width. The flux density in the stator tooth at the gap surface should not exceed 1.8 Tesla for both types of alternators; otherwise the tooth losses will be excessive.

Flux density in stator teeth at gap surface,

$$B_{ts} = \frac{\phi}{b_{ts} \times L_i \times N_t}$$

where N_t = the number of teeth per pole arc

Width of the teeth,

$$b_{ts} = \frac{B_g \tau_s}{B_{ts} \times K_{Fe}}$$

Width of the slot,

$$b_{s1} = \frac{\pi(D + 2h_{os} + 2h_w)}{N_s} - b_t$$

$$b_{s2} = \sqrt{4A_{su} \tan\frac{\pi}{N_s} + b_{s1}^2}$$

$$A_{su} = \frac{\pi d_{co}'^2 a_p n_s}{4 \times K_{fill}}$$

$$h_s = \frac{2A_{su}}{b_{s1} + b_{s2}}$$

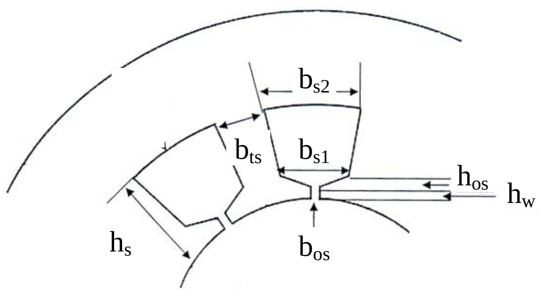

Fig.1. Main Dimension of Stator Slot and Core

For round wire, choose $K_{fill} \approx$ 0.35 to 0.4 below 10 kW and 0.4 to 0.44 above 10 kW.

Normally, the depth of the stator slot varies from 4 to 5 times the width of the slot.

Mean Length of Turn

Mean length of turn for double layer stator winding of synchronous machine is assumed to be made up of the following. The mean length of stator turn,

$$l_{mt} = (2L + 2.5\tau_p + 0.05 \times kV + 0.15)$$

Resistance of Stator Winding

The resistance of the stator winding can be calculated as given below.

Resistance of stator winding,

$$R_s = \frac{\rho l_{mt} W_{ph}}{a_s}$$

where ρ = resistivity

a_s = sectional area of stator conductor, [mm^2]

Calculation of Eddy Current Losses

Eddy current losses in conductors can be calculated from the design data of stator slot according to the following the procedure.

Find out average loss factor,

Average loss factor,

$$K_{dav} = 1 + (\alpha\, h_c)^4 \frac{m_c^2}{9}$$

$$\alpha = \sqrt{\frac{\text{copper width in the slot}}{\text{slot width}}}$$

where h_c = depth of the strand or conductor (as the case may be)

m_c = number of conductors in the slot depth

Calculate eddy current loss,

Eddy current loss = $(K_{dav} - 1) \times$ Copper losses

Stray load losses for the motor may be taken approximately 15 percent of the total copper losses and eddy current losses.

VI. CONSIDERATIONS OF PERMANENT MAGNET ROTOR

The most commonly used construction for the permanent magnet machines is the rotor construction type which has the permanent magnets located on the rotor surface. In a surface magnet machine, the magnets are usually magnetized radially. Due to the use of low permeability (μ_r = 1 to1.2) Nd-Fe-B rare earth magnets the synchronous inductances in the d and q axis may be considered to be equal which can be helpful while designing the surface magnet machine. Obtaining an optimum magnet design often involves experience and tradeoffs.

The B-H Curve in Designing

The three most important characteristics of the B-H curve are the points at which it intersects the B and H axes (at B_r - the residual induction - and H_c - the coercive force - respectively), and the point at which the product of B and H are at a maximum (BH_{max} - the maximum energy product).B_r represents the maximum flux the magnet is able to produce under closed circuit conditions. In actual useful operation permanent magnets can only approach this point. H_c represents the point at which the magnet becomes demagnetized under the influence of an externally applied magnetic field. BH_{max} represents the point at which the product of B and H, and the energy density of the magnetic field into the air gap surrounding the magnet, is at a maximum. The higher this product, the smaller need be the volume of the magnet.

The Magnetic Permeability

The relative magnetic permeability is the ratio of the magnetic flux density to magnetic field intensity at any point on the demagnetization curve, i.e,

$$\mu_{rec} = \frac{B_r}{H_c} = \mu_0 \mu_{rrec}$$

where, the relative recoil permeability is 1.

The magnetic flux density produced in the air gap l_g by a PM with linear demagnetization curve and its height h_M placed in a magnetic circuit with infinitely large magnetic permeability and air gap g is, approximately,

$$B_g = \frac{B_r}{1 + \mu_{rrec} l_g / h_M}$$

Sizing Procedure and Main Dimensions of Permanent Magnet

The volume of all PMs used in a motor is:

$$V_M = p h_M w_M l_M$$

depends on the quality of PM material(maximum energy). In above equation p is the number of poles, and $h_{M,}$, w_M, and l_M are the height, width and length of the PM, respectively. The output power of a PM synchronous motor is proportional to V_M. The maximum electromagnetic power developed by PM synchronous motor can be expressed as follows:

$$P_{max} = \frac{\pi^2 \xi f B_r H_c V_M}{2 k_f k_{ad} (1+\varepsilon)}$$

where, k_f = form factor of the rotor

k_{ad}= d-axis armature reaction factor

ξ = coefficient of utilization of the PM

f = input frequency

B_r= remanent magnetic flux density

H_c= coercive force

The volume of PMs is

$$V_M = c_v \frac{P_{out}}{f B_r H_c}$$

$$c_v = \frac{2 k_{ocf} k_f k_{ad} (1+\varepsilon)}{\pi^2 \zeta}$$

where,

$$k_f = \frac{4}{\pi} \sin \frac{\alpha_i \pi}{2}$$

$$k_{ad} = \frac{k_{fd}}{k_f}$$

VII. COMPARISON OF RESULT DATA FOR PERMANENT MAGNET SYNCHRONOUS MOTOR 50 KW USING DIFFERENT MAGNET

Table.1. Result Data Sheet for Permanent Magnet Synchronous Motor 50 kW Using NdFeB Magnet,$SmCo_3$ Magnet and Sm_2Co_{17} Magnet

Specification	Symbol	Unit	Value
Full Load Output	P_o	kW	50
Line voltage	V	Volts	500
Phase	-	-	3
Frequency	f	Hz	200
Speed	n	r.p.m	3000

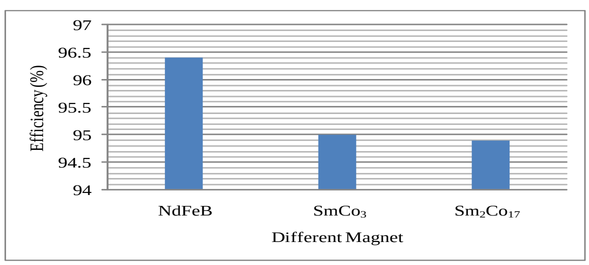

Fig.2. Efficiency of 50 kW PMSM for Different Magnet

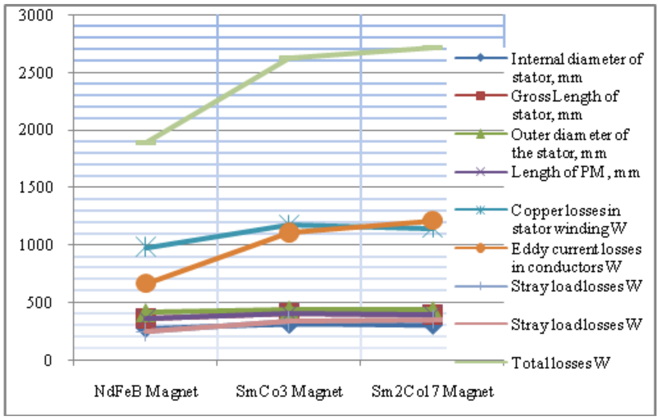

Fig.3.Permanent Magnet Synchronous Motor 50 kW Using NdFeB Magnet,$SmCo_3$ Magnet and Sm_2Co_{17} Magnet

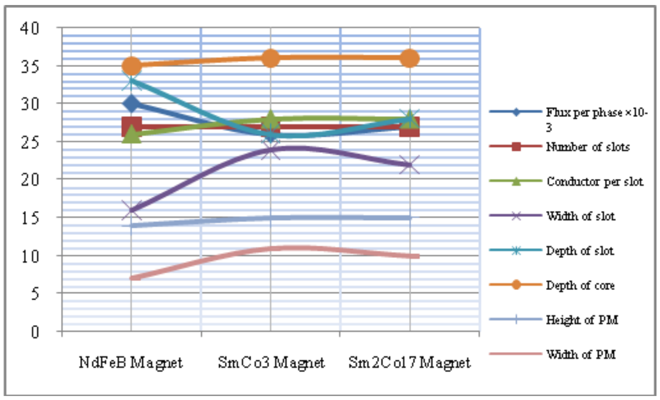

Fig.4. Permanent Magnet Synchronous Motor 50 kW Using NdFeB Magnet,$SmCo_3$ Magnet and Sm_2Co_{17} Magnet

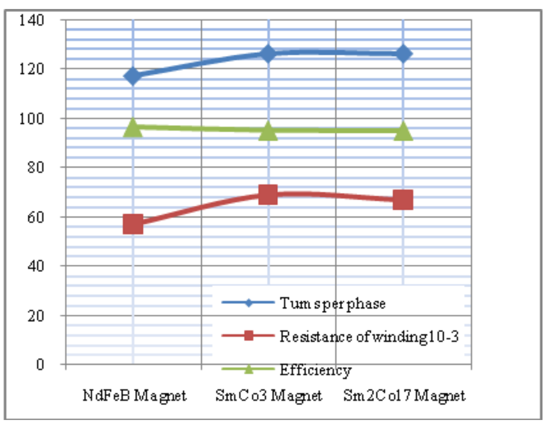

Fig.5.Permanent Magnet Synchronous Motor 50 kW Using NdFeB Magnet,$SmCo_3$ Magnet and Sm_2Co_{17} Magnet

The Fig.2 shows the efficiency of the 50kW permanent magnet synchronous motor with different magnet. The different type of permanent magnet materials are buried in the rotor of PMSM. By changing the magnets, the efficiency of the PMSM is also changed. From Fig.2 and designed data sheet Tables, the efficiency of the PMSM with NdFeB magnet is the best.

VIII. CONCLUSION

Permanent magnet synchronous motors (PMSMs) have been playing an important role in high performance drive systems. There is the need to develop technical knowhow on the design and construction of the PMSMs in Myanmar. This thesis takes the first step towards this direction. In general, the design of a PMSM involves the design of both stator and rotor. The design considered in this thesis is 50kW, 3000 rpm PMSM. In this thesis permanent magnet synchronous motor is designed for hybrid electric vehicle. The total mass of the electric vehicle is 500kg. The maximum velocity for the hybrid electric vehicle is 5 m/s and acceleration is 20 m/s^2. By changing the magnet material, not only the internal diameter of the stator and gross length of the stator but also the efficiency of the motor is also changed. As the magnetic flux density of the different magnet materials are not the same, the output coefficient is changed and other parameters concerned with the output coefficient are also changed. In this design, the NdFeB is chosen magnet to bury on the surface of the rotor because it has high efficiency compared with other magnet. The efficiency of the PMSM used NdFeB magnet is 96.4 per cent. The design of PMSM is suitable for HEV.

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